


# Developing a mobile application-based particle image velocimetry tool for enhanced teaching and learning in fluid mechanics: A design-based research approach

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## Funding information

U.S. Office of Naval Research Navy and  
Marine Corps Science, Technology,  
Engineering & Mathematics (STEM)  
Education, Outreach and Workforce  
Program, Grant/Award Number: Award  
N000141812770

## Abstract

A robust and intuitive understanding of fluid mechanics—the applied science of fluid motion—is foundational within many engineering disciplines, including aerospace, chemical, civil, mechanical, naval, and ocean engineering. In-depth knowledge of fluid mechanics is critical to safe and economical design of engineering applications employed globally everyday, such as automobiles, aircraft, and sea craft, and to meeting global 21st century engineering challenges, such as developing renewable energy sources, providing access to clean water, managing the environmental nitrogen cycle, and improving urban infrastructure. Despite the fundamental nature of fluid mechanics within the broader undergraduate engineering curriculum, students often characterize courses in fluid mechanics as mathematically onerous, conceptually difficult, and aesthetically uninteresting; anecdotally, undergraduates may choose to opt-out of fluids engineering-related careers based on their early experiences in fluids courses. Therefore, the continued development of new frameworks for engineering instruction in fluid mechanics is needed. Toward that end, this paper introduces mobile instructional particle image velocimetry (mI-PIV), a low-cost, open-source, mobile application-based educational tool under development for smartphones and tablets running Android. The mobile application provides learners with both technological capability and guided instruction that enables them to visualize and experiment with authentic flow fields in real time. The mI-PIV tool is designed to generate interest in and intuition about fluid flow and to improve understanding of mathematical concepts as they relate to fluid mechanics by providing opportunities for fluids-related active engagement and discovery in both formal and informal learning contexts.

## KEYWORDS

app, engineering education, flow visualization, fluid mechanics, mobile learning, PIV

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## 1 | INTRODUCTION

In the United States, fluid science principles and fluids engineering applications are rarely, if ever, introduced at the secondary (i.e., high school) level; early undergraduate courses in fluid mechanics are commonly considered by students to be among the most challenging due to the abstract nature of fundamental fluids concepts and principles and the depth of mathematical background needed to solve fluids-related engineering problems [4,38,51]. For example, problem solving in fluid mechanics frequently requires students to apply multi-variable calculus to derive partial differential equations and discern relationships among variables in symbolic form for analytically determinant fluid flow applications. Moreover, fundamental fluids engineering textbooks almost exclusively portray accompanying time-averaged, two-dimensional (2D) flow-field renderings and leave out illustrations of three-dimensional, instantaneous, or time-dependent flow structures that are too complex to solve analytically. As a result, early fluid mechanics courses tend to be mathematically focused and less representative of more esthetically interesting flows commonly witnessed in everyday life. Not surprisingly, undergraduates often characterize these courses as mathematically onerous, conceptually difficult, and esthetically uninteresting [16,51]. In one study, traditional fundamental fluid mechanics courses were shown to negatively affect undergraduates' self-efficacy for studying fluids and attitudes about the value of studying fluids as an engineer [16].

In contrast to mathematical problem solving, visual experiences have been shown to promote deeper conceptual understanding and improved perception, or "intuition," about fluid flow. These deeper understandings are, oftentimes, what makes the study of fluid mechanics exciting, transferable, and even inspirational. For example, previous studies have reported on positive undergraduate affective outcomes (i.e., interest and attitudes) provided by fluid mechanics instruction that engaged engineering undergraduates across interdisciplinary majors in visualizing, imaging, and conceptualizing naturally occurring, authentic flows [16,39]. Results showed that engineering undergraduates who participated in flow visualization activities displayed an improved appreciation of fluid flow and experienced attitudinal shifts in favor of the study of fluid mechanics as engineers [16,39]. Hertzberg et al. [16], for example, reported that

Students write to the instructor years later [after taking the flow visualization course], enthusing about seeing mixing in a liquid soap dispenser or vortexes in an unusual cloud. This

never happens with students from the same instructor's traditional fluid mechanics courses.

Likewise, Rossman and Skvirsky [39] shared reflections provided by undergraduates who participated in their flow visualization course: "As the semester progressed, I began seeing fluid flow everywhere, pointing out examples to all of my friends, who also caught on to the trend." Others described how undergraduates with no prior instruction in fluid mechanics displayed improved perception of fluid flows after visually sorting (e.g., laminar, turbulent) photographic images of authentic flows [15]. According to Goodman et al. [15], improved perception was related to enhanced conceptual understanding and a greater capacity to transfer this understanding to new settings.

Other researchers have studied the effects of interactive flow visualization and analysis activities, including computational fluid dynamics (CFD), particle-image velocimetry (PIV), and scientific computing modeling tools, on affective and cognitive student outcomes in fluids-related courses. For example, Nair et al. [31] found that engaging undergraduate biomedical engineering students in endovascular device testing via hands-on flow visualization and medical data analysis—using a commercially available, integrated computer-aided design, CFD, and PIV tool called HemoFlowTM—statistically improved student understanding of biofluid concepts. Neves [32] showed that the integration of scientific computational modeling tools within undergraduate courses in fluids and thermodynamics improved affective (i.e., interest) and cognitive (i.e., abilities to construct, explore, and understand hydrostatic pressure mathematical models) student outcomes by promoting deeper, more meaningful and structured learning while reducing conceptual misconceptions about physics and mathematics knowledge. Xiao [51] proposed a new instructional approach, called "CFD teaching," that engages students in numerical CFD simulations to increase student motivation for learning through flow visualization, deepen student conceptual understanding through the CFD solution process, expand classroom experimental content through numerical simulations, and prepare students for the future of work by training them to use CFD tools.

Along with key advancements in fluid mechanics education, current capabilities of today's smartphone technology—along with the sheer ubiquity and popularity of these mobile devices—have begun to influence education more broadly. Widespread acceptance of mobile devices as learning tools among educators and students at all levels have led to new approaches for implementing mobile technology in education [3]. Just a few examples include an augmented reality wordbook

smartphone application for kindergarteners (ARWAK) [19], a high-school biology laboratory activity to investigate animal thermoregulation using smartphones and inexpensive thermal camera attachments [49], and mobile applications for teaching English, a foreign language [24]. Moreover, mobile applications are also emerging as powerful tools in engineering education for engaging tech-savvy students in the creative application of engineering concepts and principles to solve complex problems through processes of *simulation* (i.e., solution designing and algorithm visualization) and *experimentation* (i.e., use of mobile device as a measurement tool as well as a source of information about measurement) [18]. Examples of mobile applications developed specifically for engineering education include an automator simulator to teach college-level courses on the theory of computation [41], a mobile educational platform to teach undergraduate- and graduate-level courses on speech signal processing [53], and a mobile learning tool to control a microgeneration system for a course on advanced thermal systems [12].

In sum, advancements in fluids mechanics instruction, coupled with the burgeoning development of mobile applications specifically for engineering education, have led us to conceive of the mobile instructional particle image velocimetry (mI-PIV) learning tool for fluids engineering education. In light of newer understandings about the importance of visualization-based activities in fluids mechanics, we contend that engineering instruction can more readily excite key aspects of student engagement—including internal motivation, interest, and curiosity—through visual exploration of authentic (e.g., naturally occurring, transient) fluid flows. Rapidly advancing and ubiquitous mobile device technology (i.e., computation and imaging capabilities) now enables real-time visual exploration and experimentation, using state-of-the-art flow visualization and optical measurement techniques (i.e., PIV) at the individual student level. Therefore, we present mI-PIV, a low-cost, open-source mobile application-based educational tool that provides novice learners capability to visualize flow structures and experiment with flow design parameters using state-of-the-art PIV techniques. *We hypothesize that mI-PIV will interest students in the study of fluid mechanics and promote deeper understanding of fundamental fluid flow concepts and measurement techniques through hands-on experimentation and guided user microinstruction.* Moreover, we envision that mI-PIV will help us to foster a more technologically advanced workforce by engaging young learners with 21st century computing tools and techniques that are critical to advanced research and practice within science and engineering [39].

## 2 | BACKGROUND

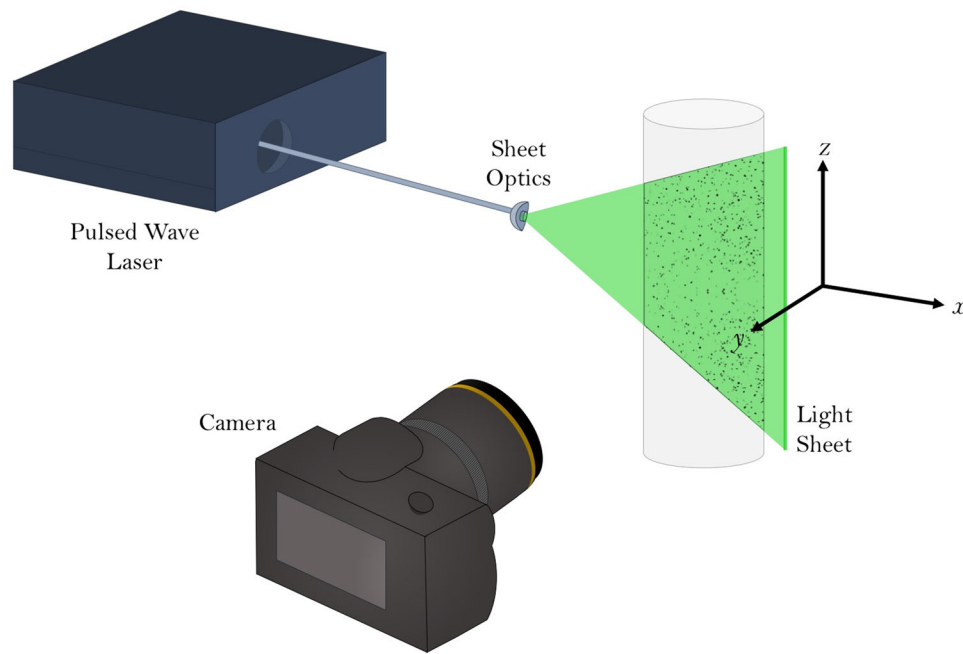
### 2.1 | PIV: Overview

The year 2014 marked the 30th anniversary of the scientific research community's realization of the optical flow visualization and measurement technique called “particle image velocimetry” or “PIV” [1]. Initially developed as a method for visualizing complex flow substructures within mathematically indeterminate, turbulent flows that are otherwise invisible to the naked eye, PIV is an optical flow measurement technique that uses statistical analyses of precisely timed image data to compute instantaneous velocity vector fields that represent and describe how the flow moves. Aided by fast-paced technological advancements in digital imaging, computer processing, and high-energy lasers, PIV has become widely accepted as a robust method for accurately measuring and visualizing flow field dynamics [1,25].

Common laboratory 2D PIV systems consist of only two components: a high-energy pulsed wave (pw) laser—equipped with a timing unit and a cylindrical lens that spreads the laser light into a thin “sheet”—and a digital camera (Figure 1). Expensive, high-energy pw lasers are used in laboratory-grade (LG) PIV systems to provide high illumination over a short imaging time to reduce image noise and particle image blur that hampers image cross-correlation and reduces system accuracy. The pw laser sheet illuminates small, neutrally buoyant particles (i.e., “seeds”) that move with the currents of flow and are imaged by the camera. Modern PIV software algorithms employ cross-correlation and subpixel interpolation to process the time-dependent particle image pairs and generate 2D vector maps of fluid velocity, as well as compute and map other flow parameters that can be mathematically derived from flow velocity measurements (e.g., vorticity). Attesting to the ongoing and expanding development, application, and popularity of PIV techniques, use of PIV now extends beyond the boundaries of traditional fluid mechanics research into other fields, such as zoology, oceanography, and marine biology [43]. As a measurement technique, PIV remains a robust area for research; continuing advances in imaging technology, laser hardware, and algorithm development enable researchers to expand the capabilities of PIV (e.g., stereo PIV, holographic PIV, and tomographic PIV) even after more than 30 years.

### 2.2 | PIV: Strengths and limitations

PIV gained prominence within the scientific research community due to its many advantages as an unobtrusive *flow field* measurement technique. Since PIV provides

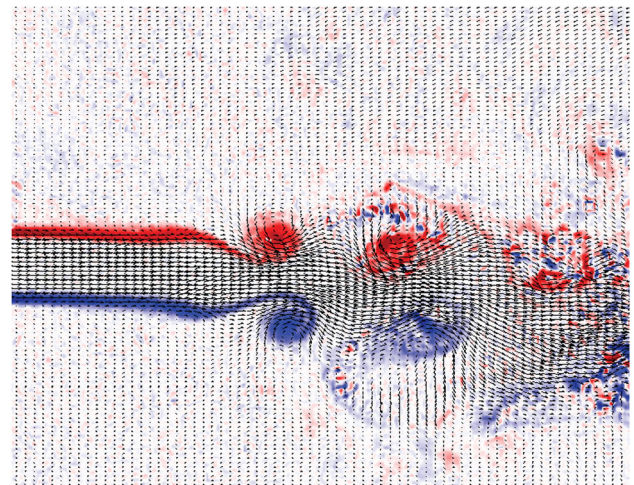


**FIGURE 1** Two-component laboratory PIV system consisting of a laser/timing unit with attached cylindrical lens and a digital camera. The pw laser is fired in the horizontal ( $x$ ) direction and spreads into a sheet in the vertical ( $y$ ) direction after passing through the sheet optics. The camera is oriented perpendicular to  $x$ - $y$  laser sheet ( $z$ -direction). Image data are sent to a standalone computer (not shown) equipped with PIV software for image preprocessing, calculation, and postprocessing of velocity vector fields. PIV, particle image velocimetry; pw, pulsed wave

instantaneous flow field measurement, it is not limited to the time-based, localized data acquisition that characterizes sensor or probe-based flow measurement techniques. Because PIV output is useful not only for quantifying flow velocity, but also for seeing instantaneous flow structure [42] (Figure 2), PIV is uniquely suited for improving understanding of fluid flow concepts using authentic or real examples, experimentation, and “what if” activities, and design ideation and troubleshooting. As an optical imaging technique, the unobtrusive nature of PIV can lead to higher accuracy and repeatability for PIV measurements as compared to localized probe-based measurements. Finally, PIV is a flexible technique in that it can be applied equally well across a range of flow regimes (i.e., laminar, transition, turbulent) in liquids as well as gases, and over a large range of spatial scales. Together, these strengths have resulted in PIV being “...the only velocity-measuring system used in many fluid dynamics laboratories” today [43].

Despite its unique strengths, PIV has several inherent limitations that serve as the reason that “PIV is a technique synonymous with compromises” [23]. PIV’s most notable limitation is its dynamic velocity range (DVR). DVR is the ratio of the maximum measurable velocity—a function of maximum allowable particle displacement within each interrogation window on the paired images—to

the minimum measurable velocity—the smallest measurable particle displacement between individual pixels in the paired images and a function of the PIV algorithm used to process the image pairs.



**FIGURE 2** A 2D velocity vector field of a submerged jet undergoing laminar to turbulent transition measured using a laboratory PIV system. Black arrows indicate magnitude and direction of flow velocity. Red and blue shaded areas represent areas of positive and negative flow vorticity, respectively. Figure reprinted from Smith [42] with permission. 2D, two dimensional; PIV, particle image velocimetry; pw, pulsed wave



The earliest PIV systems, in existence circa the mid-1980s, suffered from DVR values as low as 5–10 [1]. In contrast, point pressure sensors and probes, the historical “go to” method for fluid flow velocity measurement before the development of PIV, commonly have DVR values of 1,000,000. Modern digital imaging hardware and advanced software algorithms currently enable PIV DVR values as high as 160–200 [1,43]. Because DVR limitations necessitate a priori optimization of optical and experimental flow parameters (i.e., field of view, time between camera images) to maximize output velocity resolution, PIV can be difficult—if not prohibitive—to implement among novices without expert guidance and oversight. In addition to limitations on DVR, capital costs and maintenance expenses of traditional PIV systems have further limited its application outside of academic and industrial research environments.

### 2.3 | PIV: Prior applications in engineering education

The prominence of PIV within science and engineering has led popular fundamental engineering fluids textbooks to begin to highlight PIV techniques [9]. Unfortunately, broad application of PIV as an instructional tool remains limited due to cost—basic two component PIV systems cost on the order of \$100,000 [7] or 60,000–100,000 EUR [11]—and safety concerns such as (a) the need for large, delicate, and expensive equipment (i.e., imaging optics, high-power lasers, and robust computers) that are difficult to procure/operate/maintain; (b) reliance on expensive proprietary software for PIV computations; (c) eye safety hazards presented by the use of high power (Class 4, >500 mW) pulsed lasers to illuminate seed particles for imaging; and (d) the required know-how to operate and maintain optical and laser hardware.

Several commercially available PIV systems, including ePIV™, FLOWCOACH™, MiniPIV™, HEMOFLOW™, and THERMOFLOW™, have been developed for educational use via funding from the National Science Foundation Small Business Innovation Research Program [17]. ePIV™ was realized over a decade ago for use in fluids mechanics laboratories as part of interactive design, model (using computational fluid dynamics), and test (using PIV) process [29,34]. This “black box” PIV system enables students to visualize and quantify external laminar flows over interchangeable flow inserts or shapes (i.e., airfoils, steps, cylinders). The sealed ePIV™ system consists of a printed circuit board-mounted digital camera, a Class 4 laser with optics, a variable speed water pump and reservoir, a flow circuit, and interchangeable flow inserts all housed in a ruggedized desktop chamber. Due to safety and equipment

maintenance concerns, ePIV™ users are restricted from accessing most components of the system; users may adjust only the water level in the flow circuit (i.e., adding water), the seed density (i.e., adding flow particles), and the choice of flow insert. During operation, camera image data are exported via a USB port to a networked computer or system of computers. With access to proprietary FLOWEX™ web-based software, PIV calculations are performed and results are provided to users in graphical and/or tabular form. The advantages of ePIV™ include that the user does not need in-depth knowledge of PIV to use the system. While ePIV™ has proven successful in showcasing the value of PIV-based experimentation within the engineering design process in undergraduate fluids courses, system capital costs, classroom networking requirements, and restrictions to the type of flows (i.e., predetermined external flow over shaped inserts) that can be explored have limited its adoption to large universities [29,34].

The FLOWCOACH™ [17] system consists of a recirculating water loop, flow rate and pressure measurement capability, and an integrated digital camera to visualize laminar, transition, and turbulent flow through interchangeable flow inserts using air bubbles and to conduct laminar PIV analysis using seed particles and FLOWEX™ software. The miniPIV™ system [17] includes a digital camera with synchronizer and articulated mounting arm, pulsed light source (100-mW Class 3B laser) with synchronizer, tilt-adjustable mount and heatsink, optical breadboard and mounts, and proprietary FLOWEX™ software for conducting standalone PIV experiments of the user's choosing. Because Class 3B lasers are not appropriate for educational use—Class 3B lasers require eye protection that eliminates much of the visual aspect of PIV—the miniPIV™ system is also equipped with a light-emitting diodes (LED) illumination option.

The HEMOFLOW™ system [17] combines the LED-based miniPIV™ system with digital flow rate control and pressure measurement capability for experimentally exploring biofluid mechanics of stenosed vessels and mechanically tilting disc heart valves within a closed flow loop. The HEMOFLOW™ flow loop provides access for use of interchangeable, custom-designed blood vessel phantoms and is fully portable for classroom use. Like the HEMOFLOW™ system, the THERMOFLOW™ system [17] combines the LED-based miniPIV™ system with a FLIR thermal imaging camera to provide dynamic flow and temperature visualization over interchangeable flow model inserts in both air and water. THERMOFLOW™ provides temperature, flow rate, and pressure measurement using a digital data acquisition system, temperature visualization using the thermal imaging camera, and laminar, transitional, and turbulent flow visualization using

the miniPIV™ system. Like the HEMOFLOW™ system, THERMOFLOW™ is portable to enable use in multiple classrooms and courses.

Other researchers (Table 1) have focused more explicitly on lowering costs and increasing the modularity of educational PIV systems. For example, Ring and colleagues [37,38] developed a low-cost (\$709), modular PIV system for educational use with laminar (i.e., lower speed) flows (due to camera frame rate and resolution), primarily for use in undergraduate research projects, capstone design projects, and fluid mechanics laboratories. This system comprises a continuous wave (cw) 100-mW (Class 3B) laser pointer, a Casio EX-ZR100 camera, Avidemux® video editing freeware used to pull individual frames from the video recording, a student version of MATLAB®, and an open-source tool called PIVlab [46] (for MATLAB®) for computing velocity vector fields using PIV algorithms. The authors emphasize that system modularity makes it possible to easily upgrade or customize the system for particular flow applications, including turbulent flow. Budd and Howison [7] developed a low-cost (\$2,286) educational PIV system for use

in undergraduate fluids laboratories, which comprises a 150-mW cw laser pointer and laser safety glasses (for use with Class 3B laser), light sheet optics, Casio EX-R1 camera, student version of MATLAB® and PIVlab freeware for computing PIV algorithms, and microspheres for seed particles. The authors note that limited camera resolution at higher frame rates (i.e., 1,000 fps) is the limiting factor for this design. Ryerson and Schwenk [40] developed a low-cost (\$739–\$859) PIV system for biomechanics research, noting that the same system could also be used for teaching in laboratory environments [40]. The system comprises a >75-mW cw laser (Class 3B) with optics, Casio EX-FH100 camera, Avidemux® video editing freeware, Aha-View® image converting freeware, and a student version of MATLAB® and PIVlab freeware for computing PIV algorithms. It should be noted, in all systems, the cost of purchase and maintenance of computer for data processing is not included in the reported system costs.

Prior work (Table 1) highlights clear interest in engaging today's engineering students using state-of-the-art PIV flow visualization and measurement techniques

**TABLE 1** Prior work related to the development and use PIV systems in education

Authors and date	Camera	Laser	Software	System cost
Ökçay and Öztekin [34]	Not specified	Class 4 (>500 mW)	ePIV™	Based on implementation (number of software seats)
Medina et al. [29]	Encased	Power not specified	Proprietary FLOWEX™	
	Inaccessible to the user	Encased	(system works only with this software)	Requires online quote
		Inaccessible to the user		
Ryerson and Schwenk [40] <sup>a</sup>	Casio EX-FH100	Class 3B 75 mW minimum Continuous wave Light sheet optics	MATLAB® (student license) PIVlab freeware Avidemux® freeware Aha-View® freeware	\$739–\$859 Modular
Ring et al. [37]	Casio EX-ZR100	Class 3B	MATLAB® (student license)	\$709
Ring and Lemley [38]	1000 fps maximum	100 mW Laser pointer Continuous wave	PIVlab freeware	Modular
Nair et al. [31]	Not specified	Class 3B 1,000 mW Laser pulsed wave OR LED illumination	HEMOFLOW™ Proprietary FLOWEX™ (system works only with this software)	Based on implementation (number of software seats) Requires online quote
Budd and Howison [7]	Casio EX-R1	Class 3B 150 mW Laser pointer Continuous wave Safety glasses Light sheet optics Microspheres	MATLAB® (student license) PIVlab freeware	\$2,286 Modular

Note: Computer for data processing not included in reported system costs.

Abbreviations: LED, light-emitting diodes; PIV; particle image velocimetry.

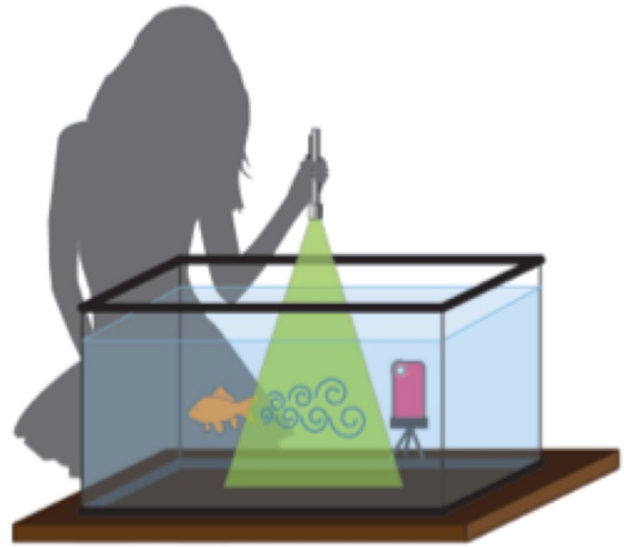
<sup>a</sup>Developed for research use; noted as having application in education.

[7,14,29,31,34,37,38,40]. Importantly, this study demonstrates three important results. First, it provides evidence that PIV systems can be realized for education using economical and safer, lower power (Class 3B) cw lasers or illumination with LEDs in combination with commercial-grade video cameras. Second, prior work indicates a shift toward use of low-cost PIV algorithms and low-cost software (i.e., PIVlab is free with MATLAB® license), indicating a realization that the cost burden of proprietary PIV software must be removed to realize low-cost systems. Third, work to date demonstrates the importance of system modularity and flexibility so that educational PIV systems can be implemented as shared resources across academic departments and colleges, such as within engineering courses, laboratory activities, undergraduate research and capstone design projects, and even informal activities with nonengineering students or younger learners.

### 3 | MOBILE INSTRUCTIONAL PIV

Despite notable advancements, PIV-based instruction in engineering education remains the exception, rather than the rule. Slow diffusion within engineering education suggests that a new developmental framework for educational PIV is needed. *Based on lessons learned from prior work, we contend that the next generation of educational PIV systems will be most advantageous for both formal and informal contexts (i.e., broadly accessible, self-contained, economical, safe, and teaching and learning centered) and, thus, more likely to diffuse broadly within engineering education if based on a distributed, mobile computing architecture* (Figure 3). Recent scientific research shows that today's mobile phone cameras are capable of taking high-speed digital image recordings with adequate resolution and time sequencing for PIV algorithmic processing [2,11,42]. Specifically, Cierpka et al. [11] demonstrated the feasibility of making mobile PIV measurements for moderate flow velocities and coarse spatial resolutions—such as those encountered in industrial applications or educational contexts—using a mobile phone camera and a 1-W (1,000 mW) cw laser. This study confirms that appropriate use of cw lasers can lower PIV system expense in two ways: by reducing the system cost of the laser and by removing the need for pw laser-camera synchronization equipment [11].

Previous studies have reported on the use and benefits of mobile learning for students' performance and motivation in K-12 education [26,47]. Moreover, examples of mobile learning tool development and use within several engineering disciplines, including acoustics and vibrations [48], computer science [36], and



**FIGURE 3** ©ASEE, 2019. Conceptualized use of the mI-PIV mobile learning tool. A learner illuminates an everyday flow field using a low-power laser pointer while the mI-PIV tool captures images, processes data, and displays results as velocity vector fields for flow visualization and measurement. Figure reprinted from Authors with permission. mI-PIV, mobile instructional particle image velocimetry

structural dynamics [44], signal emerging acceptance of mobile learning within postsecondary engineering education. Although we found that available literature related to the development of mobile PIV learning tools for fluid mechanics education was limited (we did not find any in our search), our literature search did reveal work related to the development of a mobile PIV tool for the industrial fluid mechanics application of measuring surface flows (i.e., of rivers and discharges) during extreme weather events such as floods [10]. This mobile PIV device processes surface flow images, ortho-rectified using an integrated laser-projecting module, internally using JAVA-based PIV cross-correlation algorithms to output a surface velocity profile. Because the tool measures only surface velocities, complexities of a priori PIV experimental parameter estimation and set up are minimized. While the tool implements an interface to guide the user through data collection and measurement display, it does not include capability to instruct the user on fluid mechanics principles or PIV techniques. In sum, this study provides precedent for "on-the-phone" PIV image capture, pre/postprocessing, computation, and results display—using current smartphones running Android—with sufficient accuracy for industrial use. Continuing advancements of mobile device camera and processing speed will ensure that image and processing capabilities of mobile PIV systems will improve over time.

*mI-PIV design goals:* Because more mobile devices in use today employ Android operating system (OS) than other mobile operating system [27,45], we chose to design the mI-PIV application for use on the Android OS (Figure 3). Design goals for the mI-PIV application include that it

1. is free to download;
2. is open source and archived on open and accessible repositories such as GitHub;
3. initially operates completely (i.e., including image processing and algorithm computation) on the Android mobile device for broad dissemination, with available web-based options for future scale up to other operating systems (i.e., iOS);
4. provides output flow field measurement accuracy within an appropriate margin of error for educational use;
5. includes an intuitive and instructional guided user interface that:
  - a. provides users, who may be PIV novices, a step-by-step process for setting up and troubleshooting PIV experiments;
  - b. engages users in learning about PIV techniques and laser safety;
  - c. guides users in interpreting experimental PIV results to connect visual data representations with physical and mathematical concepts from fluid mechanics;
  - d. includes easy access, searchable user guide information.
6. is paired with a simple, low-cost, low-power continuous wave laser/optics system for safe and economical particle illumination in a darkened room without eye protection.

In sum, we contend that the development of a free and open-source mobile application-based PIV tool will provide easily accessible, hands-on learning opportunities for today's learners. By implementing free and open-source computational algorithms that are without third-party application dependencies and are archived on accessible repositories such as GitHub, we will remove system software cost and reduce long-term application maintenance costs. The goal is to design an intuitive and instructional mobile computing interface that will guide learners through PIV experimental setup and analytical interpretation of resultant flow data. It will help promote individual learner interest in fluid mechanics and enable greater numbers of diverse students to experiment and learn fluid concepts and PIV techniques in personalized ways. Pairing the tool with a low-cost, low-power (5 mW

maximum) easily accessible cw laser pointer will ensure safe operation even among novice learners under limited guidance and without eye protection [30]. System modularity will enable experienced PIV users to operate the tool using more powerful cw lasers or pw lasers for improved accuracy in measurement applications.

## 4 | mI-PIV DEVELOPMENT PROCESS USING DESIGN-BASED RESEARCH

As an interdisciplinary team of engineering education, mechanical engineering, and computer science researchers, instructors, and graduate and undergraduate students, we are employing design-based research (DBR) to develop the mI-PIV learning tool through an iterative process of design, implementation, and assessment [8]. DBR is characterized as being situated in a real-life educational context, focusing on the realization of significant educational intervention, and employing multiple iterations of analysis, design, development, and implementation in collaboration with cognizant stakeholders (i.e., students, instructors, researchers) to develop effective interventions and discover new design principles or theories [50]. These criteria ensure that research results can be used to improve educational practice within the design context and, likely, similar contexts—that is, both locally and globally [22,28].

Although still considered to be an “emerging” approach to research within the engineering education community, DBR gained prominence in the field of education nearly three decades ago as digital technology use became mainstream practice in the early 1990s [21]. More of a research approach than a singular, specific methodology, the essence of all DBR studies is a “...general commitment to designing and developing prototype solutions to problems of educational practice” and, as such, a “... move from a laboratory-based to a field-based science” [21]. Ultimately, DBR generates new knowledge on teaching and learning through the intentional design, development, and ongoing implementation of prototype solutions within and across research phases and among a variety of stakeholders (i.e., researchers, students, teachers, administrators, programs, etc.) who are situated in context [21]. Not surprisingly, DBR studies are commonly conducted by large, multidisciplinary teams using phased research approaches that last over several years. Only after factors affecting local implementation are believed to be understood do DBR researchers move toward broader scale evaluation of the intervention. Even at these later stages, focus remains on the evaluation of key concepts or principles discovered within varying



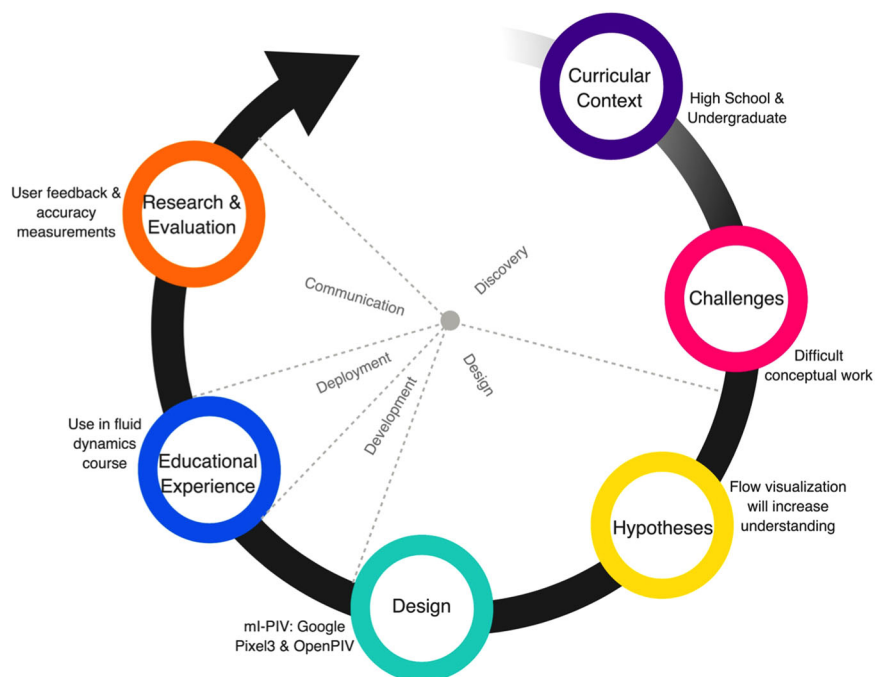
contexts, rather than on conducting large-scale experimental or quasi-experimental studies to pursue generalizable results and causal claims [21].

A basic representation of a simple DBR process (Figure 4) draws a striking comparison to the classic engineering design cycle. The DBR process begins with an educational question or problem. Researchers (who are often also instructors themselves) develop hypotheses based on educational theories, knowledge about how students learn, the learning context, and their experience, then generate potential solutions. Next, DBR researchers develop design requirements and constraints that are used to formulate and develop a contextualized intervention, in collaboration with educational stakeholders, for use within a well-defined educational context or setting. Throughout the development process, researchers engage in both planned and unplanned *design studies* in which they implement, assess and evaluate the intervention within multiple appropriate, authentic, and increasingly complex educational contexts. Data, which can be collected in a myriad of forms (i.e., both qualitative and quantitative in nature), is collaboratively analyzed and employed as the process is reinitiated and the intervention is further developed and eventually refined through subsequent iterations [5,50].

In the broad sense of this DBR project, planned systematic and iterative implementation of the mI-PIV tool will be carried out—in accordance with an approved Institutional Review Board (IRB) protocol—during Years 2–3 of the project at four primary educational sites: an undergraduate fluids engineering laboratory course, an

undergraduate fluid mechanics course, an immersive 3-week engineering camp for high-school students, and a 1-week summer engineering camp for middle school and early high school students. Students in all settings will work through custom-designed, age-appropriate, semi-structured mI-PIV exploratory sessions. Feedback and assessment data will be gathered via self-report surveys, direct observation of student engagement with the mI-PIV tool, electronic copies of student artifacts produced while using the mI-PIV tool, and/or interviews with instructors and outreach facilitators. Data will be retrospectively and collaboratively analyzed. Findings will be used to guide tool refinements, and to examine the ways that diverse learners use mobile technology to visualize and learn fluid mechanics concepts within varying contexts.

Focused on Project Year 1, this paper reports on the development of a first-generation mI-PIV prototype that includes a mobile test application and peripherals (i.e., low-power laser light source, low-cost laser sheet optics, and easy to assemble flow visualization experiments). During Year 1, we engaged in multiple, small-scale design studies that focused on implementing the prototype among design team members and potential learners (i.e., individual engineering undergraduates with IRB approval) to examine and improve coarse-grained features of the mI-PIV tool. Specifically, we conducted *flow output and benchmarking design studies* to examine (a) basic mI-PIV test application functionality; and (b) mI-PIV test application operation when coupled with safe education laser lighting levels, low-cost laser sheet optics, and



**FIGURE 4** ©ASEE, 2019. The mI-PIV design-based research (DBR) methodology. DBR is a systematic and flexible methodology aimed to improve education practice through iterative analysis, design, development, and implementation of a significant educational intervention. Figure reprinted from Authors with permission. mI-PIV, mobile instructional particle image velocimetry

education flow experiments. We also conducted inquiry-based design studies with engineering undergraduates to examine (a) intuitive and ease of mI-PIV tool use among engineering undergraduates with no PIV experience and (b) potential of the mI-PIV tool to generate interest and excitement about the study of fluid mechanics among student learners.

## 5 | YEAR 1 DESIGN STUDY FINDINGS

In this section, we present the development of the mI-PIV mobile application, including the test application, the JAVA-based application, and the guided instructional interface (GII) design. Then, we discuss findings from the flow output and benchmarking design studies and the inquiry-based design studies with engineering undergraduates conducted with the first-generation mI-PIV prototype during Project Year 1.

### 5.1 | mI-PIV mobile application development

During Project Year 1, we have developed an mI-PIV mobile test application and are engaged in the development of a JAVA-based mobile application to enable full computational functionality directly on the mobile device. We are also engaged in the development of a GII to lead learners through the PIV experimental process and provide them microlearning content about fluid mechanics principles and PIV how-to knowledge.

#### 5.1.1 | mI-PIV test application

The mI-PIV test application is developed using the Android Studio Integrated Design Environment for mobile devices running Android OS. Currently, Google Pixel 3 XL phones (30-fps video frame rate at all resolutions of 720p, 1,080p, or 4kp) with 64-GB memory are used to run the test application for operational and system-level testing and for implementation with learners. Early application development work during project Year 1 focused on realizing this “test application” (i.e., one that enables image pair capture via the mobile device, image preprocessing, algorithmic calculation and postprocessing, and display of calculated vector field) using the basic guided user interface capability provided within Android Studio. The test application has three primary functions: to (a) enable concurrent exploration of integrated system-level development issues such as

measurement accuracy/benchmarking, laser/optics system design and testing, and GII conceptual design; (b) enable upfront engagement of mI-PIV stakeholders (i.e., research team, advisory board, and learners) within DBR iterative assessment process; and (c) introduce project team computer science developers to the requirements and nuances of PIV computational processes.

PIV algorithms for the test application were developed using OpenPIV [35], a flexible suite of open source PIV image analysis and postprocessing algorithms for use with MATLAB®, C++, and Python programming languages. Specifically, the test application was coded using Python programming language since (a) Python is a freely available and open-source language and (b) project team computer science developers were experienced implementing the Python coding language. Currently, the mI-PIV test application allows for video capture from the mobile device camera, frame extraction, image parsing, and preprocessing, transfer of preprocessed images to an external server running Ubuntu 18.04 OS, advanced (i.e., multipass/multigrid with subpixel interpolation) PIV algorithmic computations and postprocessing of image data on the server, and transfer of the resultant flow field output back to the mobile device for viewing and interpretation. Development affordances of test application include the design of capability, within Android OS, for parsing images from video taken by the user with the mobile device camera, for displaying parsed images in a gallery format to the user, and for allowing the user to toggle through displayed images and select those images to be processed. The latter two capabilities are important during PIV experimental setup and are necessary to highlight for novice PIV users within the GII.

#### 5.1.2 | JAVA-based PIV application

The next step in mI-PIV development is moving to JAVA-based PIV algorithms so that PIV processing and vector output postprocessing can be accomplished directly on mobile devices running Android, instead of on an external server. We began the project thinking this step could be easily be accomplished by porting JPIV [20]—an open source software for PIV image processing and postprocessing written in JAVA—to the Android development environment. Unfortunately, we found this to not be the case; we ran into programming restrictions in JPIV based on obsolete third-party application dependencies (e.g., AWT, which is not supported in Android) that inhibit necessary modification of the JPIV computational and postprocessing algorithms. From these experiences, we made the decision to program custom PIV algorithms in JAVA instead of

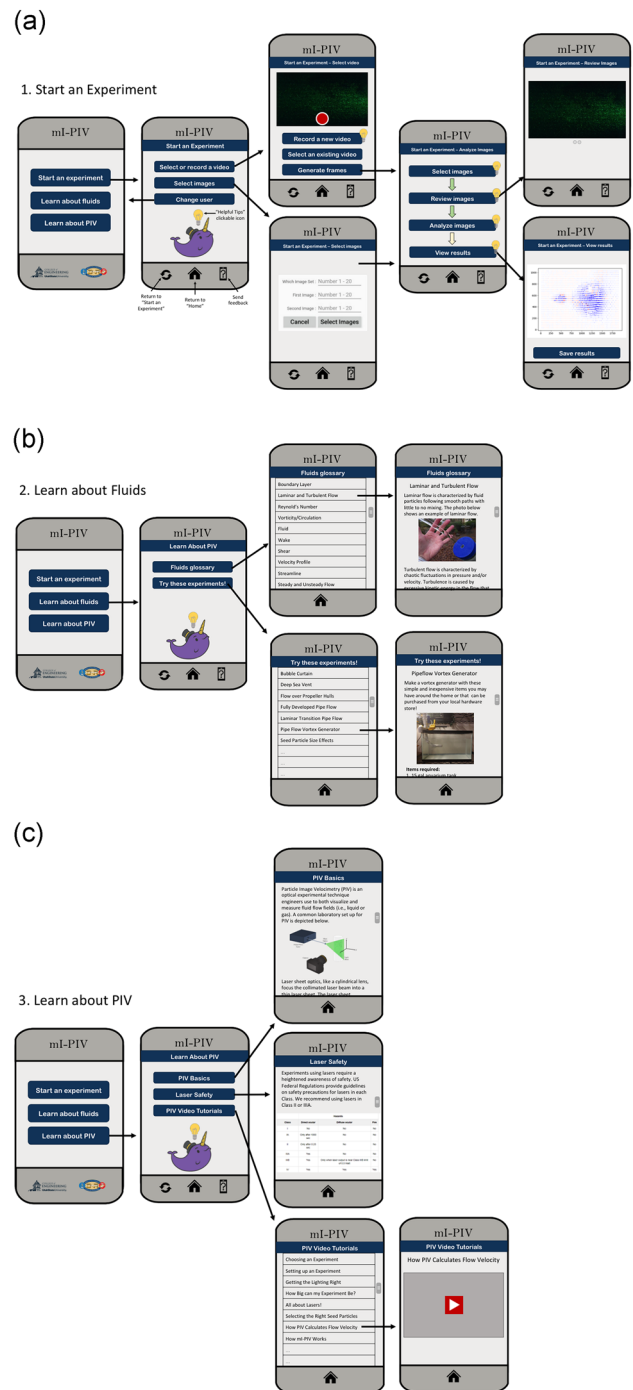
implementing JPIV. JAVA-based PIV code development is ongoing.

### 5.1.3 | Guided instructional interface

Conceptual design and JAVA code development of the mI-PIV GII have begun. The design is based on feedback received during pilot studies implementing the test application with undergraduates, as well as the team's own use of the test application. The goals of the mI-PIV-guided user interface include to (a) guide the learner through the setup of a PIV experiment that results in usable data output; (b) keep the learner apprised of experimental and computational progress so that they do not lose interest or become confused by the technical aspects of PIV; (c) provide the user optional access to PIV "how-to" information and relevant fluid mechanics content at every step of the process; and (d) assist the learner in interpreting and asking questions about the data output. The design of the mI-PIV GII is based on principles of microlearning that have been shown to improve understanding by focusing learners' attention on small units of content over a short time period [33]. Microlearning activities engage learners with "micromedia," including definitions, formulas, small pieces of text, brief video segments, mini podcasts, flash cards, and quizzes, to enable them to obtain "microcontent" [52]. Microlearning is considered to be a flexible model of learning that is able to support the needs and preferences of mobile learners [6]. The conceptual design of the mI-PIV GII is ongoing. A storyboard of the GII conceptual design is provided in Figure 5a–c.

The "Start an experiment" pathway through the mI-PIV GII is shown in Figure 5a. This pathway takes learners through the PIV image acquisition process by prompting them to record a video or select an existing video or images previously generated from a video. After image frames are parsed from the video, the learner selects two images to be used in the analysis. Image pairs can be reviewed, or "toggled," to ensure there is visual correlation between particles in each frame. Once the selected images are analyzed, the resultant velocity vector field is displayed. Results can be saved by the learner, if desired. Helpful tips and how-to information about PIV and fluids is provided throughout the "start an experiment" pathway via the light bulb icons.

The "Learn about fluids" pathway is shown in Figure 5b. This pathway provides learners with microcontent pertaining to fundamental terms and concepts fluid mechanics through the Fluids glossary. Content in the Fluids glossary is provided in micromedia formats, to include textual definitions written in everyday language,



**FIGURE 5** (a) Storyboard of mI-PIV-guided instructional interface design. Start an experiment. (b) Storyboard of mI-PIV-guided instructional interface design. Learn about fluids. (c) Storyboard of mI-PIV-guided instructional interface design. Learn about PIV. mI-PIV, mobile instructional particle image velocimetry

visual images, brief videos, equations, and existing PIV output. In addition to the Fluids glossary, the "Learn about fluids" pathway provides learners access to a repository of low-cost, easy-to-assemble flow experiments for use with mI-PIV within "Try these experiments."

Experiments developed and validated in authentic undergraduate and K-12 outreach programs during this project, including text and video instructions, parts lists, and an age-appropriate curriculum, will be archived in this repository for learner and instructor use.

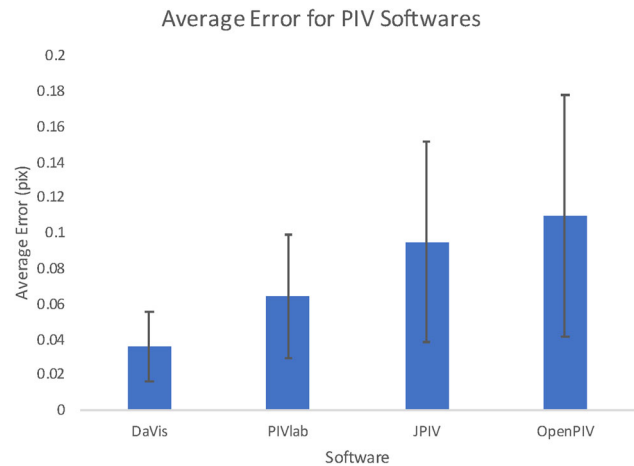
The “Learn about PIV” pathway is shown in Figure 5c. This pathway provides learners with microcontent pertaining to the fundamental aspects of PIV through the “PIV Basics” page. In addition, this pathway provides learners with microcontent on laser safety through the “Laser Safety” page, as well as brief videos that break down important things to consider when setting up PIV experiments through the “PIV Video Tutorials” page.

## 5.2 | Flow output and benchmarking design studies

We conducted three design studies related to mI-PIV flow measurement output and benchmarking using the mobile device test application. The first study compared resultant vector fields produced using standard PIV codes including DaVis [13] (commercial/proprietary), PIVlab (free with MATLAB® license), OpenPIV (open), and JPIV (open) to understand differences in computational accuracy between the three types of PIV codes (i.e., proprietary, freely available, open source). The second study examined the effects of varying cw laser power and stream-wise velocity on PIV output. The third study compared output of an mI-PIV prototype (mI-PIV test application running on a Google Pixel 3 XL 64-GB phone and a variable power cw laser diode) and an LG PIV system (i.e., high-speed camera, 150-W pw laser, and PIVlab) to understand the comparative output variation between mI-PIV as implemented within a classroom setting (i.e., 5 mW power, 30-fps video capture, demonstration flow field)—a worst case analysis in terms of mI-PIV output accuracy—and a laboratory commercial system. The purpose of these design studies was to better understand the effects of PIV system components (laser power, camera, image processing codes, flow experimental setup) on mI-PIV prototype output to inform further development of the mI-PIV system.

### 5.2.1 | Comparison of PIV code outputs using synthetic images

During the first design study, a synthetic image pair (i.e., an image pair computed using 2D velocity vector field data generated in MATLAB® from an analytically determinant flow field) was used to compute velocity vector fields using four standard PIV software packages: DaVis,



**FIGURE 6** Bar graph depicting average error (pixels) in particle displacement for each of four standard PIV software codes. Error bars represent one standard deviation from the average error. PIV, particle image velocimetry

PIVlab, OpenPIV, and JPIV. Error in pixel displacement at each pixel location in the flow field was computed by comparing the output flow field for each code to the analytical results. The average error in pixel displacement and average standard deviation computed for each software package are shown in Figure 6. Across codes, the average error of pixel displacement ranged from a minimum of 0.036 pixels (DaVis) to a maximum 0.11 pixels (OpenPIV).

We note that both the average error in pixel displacement and standard deviation of pixel displacement error computed for each proprietary code (i.e., DaVis and PIVlab) are lower than the error computed for the open-source codes (i.e., OpenPIV and JPIV). By quantifying the error induced by each type of algorithm, we are able to conclude that proprietary PIV codes result in smaller errors in pixel displacement. Therefore, the expense of proprietary codes provides for higher system accuracy and DVR. This information will help us to choose the experimental setup for the benchmarking testing for later versions of mI-PIV prototypes.

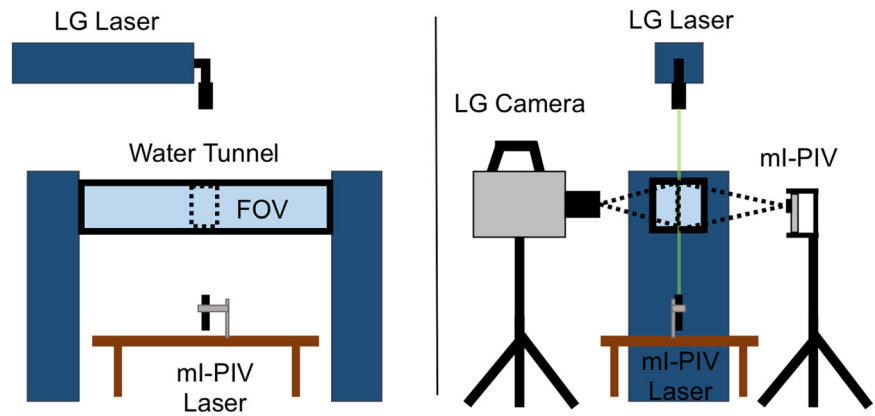
### 5.2.2 | Effect of cw laser power and flow velocity on mI-PIV test application output

During the second design study, rectangular channel flow through a recirculating water tunnel was imaged using the mI-PIV test application and the LG PIV system for the same field of view of the flow (Figure 7).

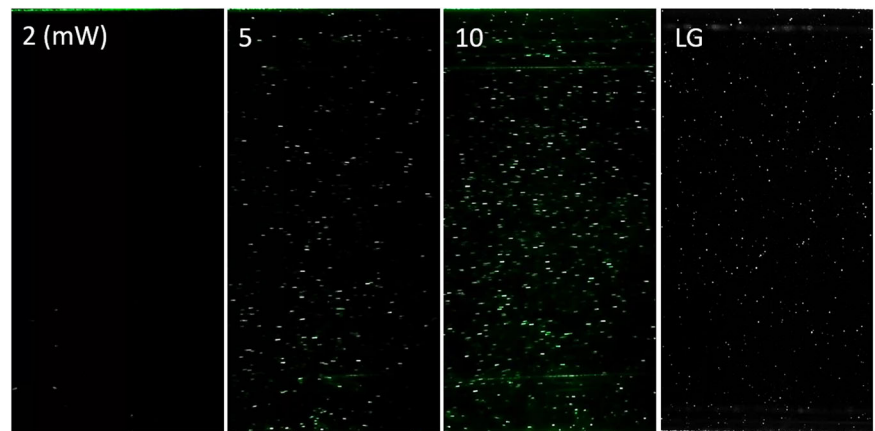
Images taken by the mI-PIV prototype at varying cw power levels (i.e., 2, 5, and 10 mW) and the LG system are shown in Figure 8.



**FIGURE 7** Water channel experimental setup front view (left) and side view (right) used to test effects of varying cw laser power and flow velocity on mI-PIV test app error. mI-PIV, mobile instructional particle image velocimetry



**FIGURE 8** Raw particle images for water channel flow field at constant stream wise velocity taken with (a) mI-PIV test app operating at three cw laser power levels (2, 5, and 10 mW) and (b) laboratory grade (LG) PIV system (far right). cw, continuous wave; mI-PIV, mobile instructional particle image velocimetry



Individual images indicate that 2-mW cw laser power is insufficient to image particles for the chosen field of view and selected seed particles (Extendspheres® HD Hollow Spheres average  $130\ \mu\text{m}$  diameter.) The 5- and 10-mW cw laser power levels do provide a substantial improvement in particle illumination for the same field of view, although particle image streaking is evident when compared to LG system case.

Image pairs taken at the same laser power levels were then averaged over 150 pairs and processed on PIVlab using multipass/multigrid and standard deviation outlier removal options to compute velocity vector fields (Figure 9). Unlike the 2-mW cw laser power case, velocity vectors computed for the 5- and 10-mW cases provide *qualitatively* (i.e., pertaining to the direction of the velocity vectors) accurate representations of the flow field as compared to the LG case.

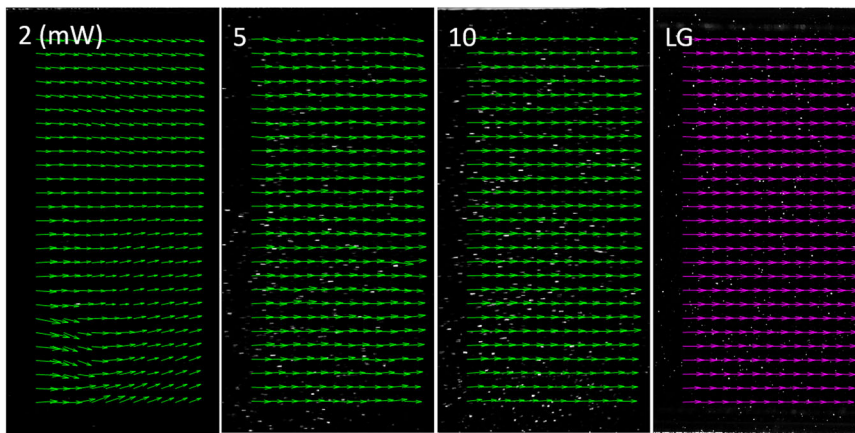
*Quantitatively* (i.e., pertaining to the length or magnitude of the velocity vectors), variation between mI-PIV test application and LG system output is seen to be function of both cw laser power and stream-wise velocity. Variation in stream-wise pixel displacement is calculated as the absolute difference between the mI-PIV and LG pixel displacements at each pixel location. Average variation in stream-wise pixel displacement is calculated by

averaging pixel displacement variations over all pixel locations on the image. Average variation in stream-wise pixel displacement as a function of mI-PIV cw laser power (i.e., 2, 5, and 10 mW) is plotted against stream-wise velocity in Figure 10. Average variation is seen to increase with (a) decreasing laser power, and (b) increasing flow velocity. For most velocities, minimum variation occurs for the highest (i.e., 10 mW) cw laser power case.

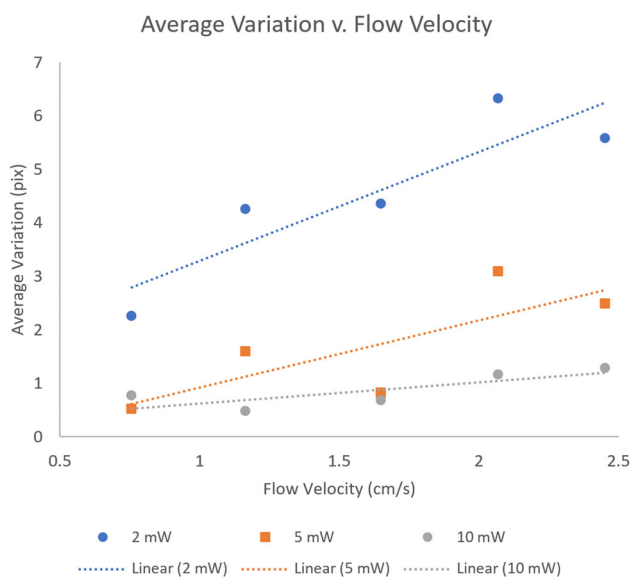
Findings represented by Figure 10 suggest that the implementation of mI-PIV as a quantitative flow measurement tool, especially at higher flow velocities, is dependent on the ability to use a higher cw laser power. Use of mI-PIV as a qualitative educational tool, however, appears feasible at cw laser powers values as low as 5 mW (Figure 9).

### 5.2.3 | Comparative use of mI-PIV in an educational context

For the third design study, output from the mI-PIV test application with the cw laser power set to 5 mW was compared to that of the output of the LG PIV system for the same test case. The test case was a demonstration



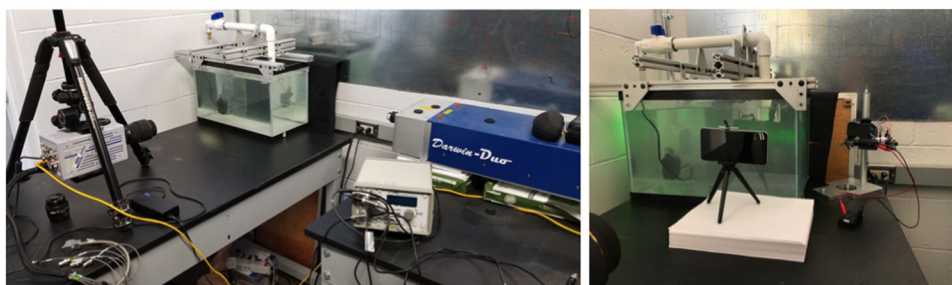
**FIGURE 9** Velocity vector fields for water channel flow field at constant stream wise velocity computed using PIVlab for (a) mI-PIV test app operating at three cw laser power levels (2, 5, and 10 mW) and (b) laboratory-grade (LG) PIV system (far right). mI-PIV, mobile instructional particle image velocimetry



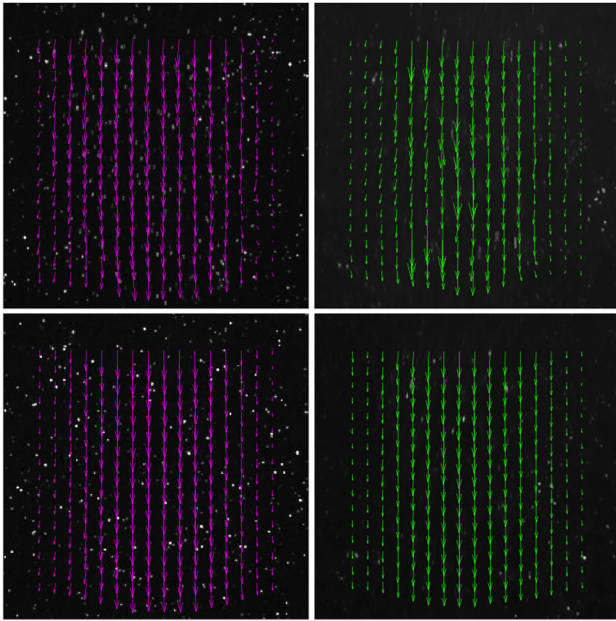
**FIGURE 10** Average variation in stream-wise pixel displacement computed using PIVlab plotted as a function of flow channel velocity for mI-PIV test app operating at three cw laser power levels (2, 5, and 10 mW). mI-PIV, mobile instructional particle image velocimetry

flow field (downward submerged water jet) constructed for classroom use (Figure 11). The purpose of this design study was to examine the combined effects of mI-PIV system components (i.e., mobile phone camera recording video at 30 fps, and 5-mW cw laser) on its output by comparing it to the output of an LG PIV system (i.e., high-speed camera, 150-W pw laser) for a demonstration flow field. For this experiment, velocity vectors fields for both the mI-PIV test application and the LG PIV system were computed using PIVlab.

Velocity vector fields and contour maps of absolute velocity for the LG PIV and mI-PIV test application are shown in Figure 12. Velocity vector field results reveal that the mI-PIV test application vector field results provide an effective qualitative representation of the flow field (i.e., directional characteristics of the flow) when compared to the LG setup. mI-PIV vectors computed from a single image pair (top row of Figure 14) show variation in magnitude of the velocity (i.e., the length of the arrows) but not in the direction of the velocity (i.e., the direction of the arrows). Similar distinct variations in magnitude are not noticed in the vector fields for the LG PIV system. Velocity vector magnitude variations for the mI-PIV system are most noticeable in the center of the



**FIGURE 11** Experimental setup for results comparison between the laboratory-grade (LG) PIV system (left) and the mI-PIV test app with 5 mW cw laser (right). Flow field is a downward submerged water jet developed as a classroom demonstration. cw, continuous wave; mI-PIV, mobile instructional particle image velocimetry



**FIGURE 12** Velocity vector fields computed using PIVlab for the laboratory-grade (LG) PIV system (left) and the mI-PIV test app with 5 mW cw laser (right) for the downward submerged water jet classroom demonstration. Top row results are computed from a single image pair. Bottom row results are averaged over 15 image pairs. cw, continuous wave; mI-PIV, mobile instructional particle image velocimetry

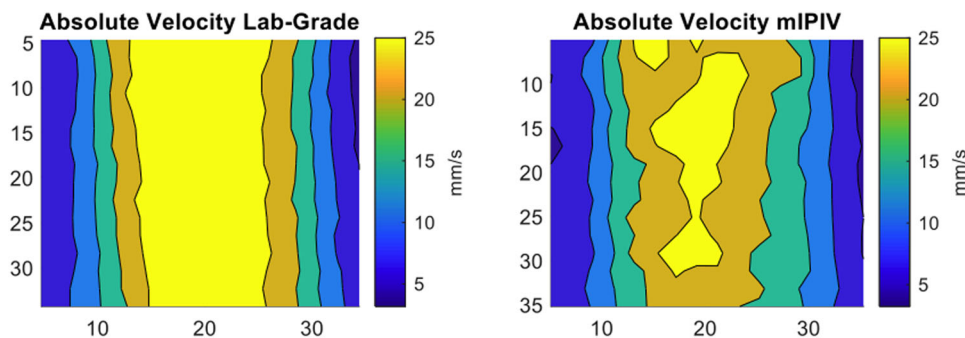
downward jet where velocity magnitudes are a maximum. This distinct (i.e., not smooth) variation in the magnitude of the velocity vectors is largely absent after averaging results over 15 image pairs (bottom row of Figure 14).

Contour maps of absolute magnitude of velocity (Figure 13) reveal spatial differences in the measured velocity magnitude between the LG PIV system and

mI-PIV test app. Spatial variations are most prominent near the center of the downward jet where velocities are a maximum.

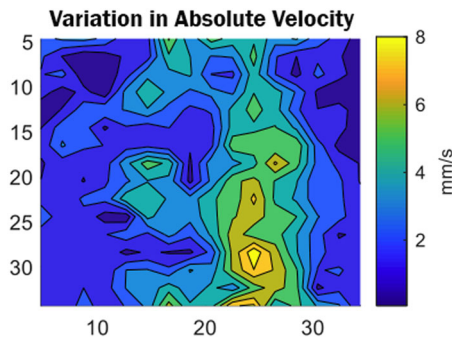
Comparison between LG PIV system and mI-PIV test application results show approximate variations of 15–30% (4–8 mm/s of 25 mm/s) within the main area of the jet. Areas of maximum variation (i.e., 30%) are small within the overall flow field (Figure 14).

From this design study, we conclude that the mI-PIV test application can provide feasible educational PIV through qualitatively accurate representations of the flow fields resulting from inexpensive, desktop flow experiments of simple flow fields built for engineering classroom and outreach contexts. This study has helped us to understand mI-PIV prototype operation in a “worst case” configuration: (a) 5 mW cw laser power (i.e., Class 3R) that is safe for use without eye protection; (b) minimum video frame rate (30 fps for Google Pixel 3 XL in regular video mode) that most smartphones capable of video recording can achieve; and (c) inexpensive demonstration flow field developed for classroom use. Follow-on work will involve testing mI-PIV at higher frame rates (slow-motion video capable of 120/240 fps) and with more complex flow fields to understand its capability range. Other work to improve mI-PIV measurement capabilities include (a) implementing image averaging (perhaps with as few as 15 image pairs to reduce or limit the computational expense associated with image averaging) when computing velocity vector flow fields directly on the mobile device; (b) exploring image preprocessing options (i.e., removing image backgrounds before processing) and use of bandpass filters to make particle images more distinct; and (c) exploring the use of macrolenses to reduce image distortion caused by wide image angles that are inherent of mobile phone cameras.



**FIGURE 13** Contour plots of absolute velocity magnitude computed using PIVlab for the laboratory-grade (LG) PIV system (left) and mI-PIV test app with 5 mW cw laser (right) for the downward submerged water jet classroom demonstration. cw, continuous wave; mI-PIV, mobile instructional particle image velocimetry





**FIGURE 14** Contour plot of absolute difference between the velocity vector magnitudes calculated for the (LG) PIV system and mI-PIV test app with 5 mW cw laser for the downward submerged water jet classroom demonstration. cw, continuous wave; LG, laboratory grade; mI-PIV, mobile instructional particle image velocimetry

### 5.3 | Inquiry-based design study with engineering undergraduates

We are conducting an ongoing design study with mI-PIV prototype among individual undergraduate engineering students to better understand how student learners intuitively (i.e., without instruction) use the mI-PIV tool to visualize and measure flow in an inquiry-based, unstructured learning environment. A primary purpose of this design study is to generate data on learner use of the mI-PIV prototype to feed it back into the design of the Java-based application and the GII. A secondary purpose of this design study is to explore the team's initial hypothesis that flow visualization via PIV on a mobile device will excite learners in the study of fluid mechanics.

In accordance with a protocol for research with human subjects from our university's institutional review board, we purposefully select engineering undergraduates at the research team's home institution who are not currently engaged in formal fluid mechanics instruction (i.e., a third-year fundamental course in fluid mechanics offered by any engineering discipline such as biological, civil, or mechanical engineering, or a fourth-year fluid mechanics laboratory, such as the one offered by the Department of Mechanical and Aerospace Engineering) to participate in the study. Participants must be undergraduates who are majoring in engineering. At the end of the session, participants each receive a \$25 electronic Amazon gift card to thank them for their time.

To conduct the study, each participant meets individually with two education researchers at a mutually agreed upon time in an on-campus laboratory where the flow experiment is located for approximately 30 min. The flow experiment used in this design study is the downward jet (Figure 11). Participants are provided a Google

Pixel 3 XL phone with the mI-PIV test application open. Participants are given a brief description of the experiment and PIV and then asked to use the mobile application to generate a velocity vector field of the submerged water jet flow. The flow experiment is turned on, the laser sheet is illuminated, and the lights in the room are turned off (necessary for PIV visualization). Once the room lights are turned off, the first researcher starts the audio/video recording to capture the learner's actions and verbal comments. The second researcher takes written observational field notes of the participant's behaviors, as well as interacts with the participant as needed, providing only minimal suggestions or responses to the participant's questions. After the session is complete, the second researcher gathers the participant's PIV output as artifact data. Qualitative data (i.e., audio/video recordings, written field notes of observations, and artifact data) are analyzed holistically to gain better understandings of the how participants used the mobile application, participant's frustrations with using the application, and as well evidence of affective learning outcomes (i.e., excitement, interest, engagement) related to the study of fluid mechanics through flow visualization.

Thus far, two undergraduate engineering students (1 male, 1 female, 2 white) have participated in this ongoing inquiry-based design study. As we engage with more participants and our dataset grows, we are finding it useful to categorize participants into two groups based on their prior experience learning fluids mechanics: those who have had no formal fundamental instruction in fluid mechanics and those who have completed a fundamental fluid mechanics course but have not completed an advanced fluid mechanics laboratory course. Our current findings are presented as those common across both groups and those particular to each group (Table 2).

Several key findings are common across participant groups. Those related to the operation of the mobile application were (a) *the poor quality of output generated from images taken with the phone*; (b) *participants not knowing how to select images pairs for PIV analysis*; and (c) *participant frustration with the time required to parse video into image frames*. All of these findings have since led to changes to the mobile application architecture. First, from these data we learned that mI-PIV users cannot take PIV images for PIV analysis with the mobile device for two reasons. First, it is difficult to hold the mobile device still enough (while pressing the button) to take a useful image pair. Second, since the button has to be pushed twice to take an image pair, the time needed to push the button twice was found to be too large for PIV calculations (i.e., the particles leave the frame between images). Based upon these findings, the application was updated to analyze only images parsed from



**TABLE 2** Findings from the inquiry-based design study with engineering undergraduates

Category	Finding with representative data excerpts
Common among groups	
Operation of mobile application	<p><b>Poor quality output from taking images as opposed to video:</b> "Hmmm...maybe let's try a video now." (Looking at poor output from analysis using two photos taken by hand)</p> <p>"On the ones where it generated the frames from the video, I thought it was more accurate than me trying to take the pictures quickly"</p> <p>(Comparing output to flow field) "I mean, that looks more right to me [than the previous frames used]"</p> <p>"I could take a video, I seem to be getting pretty different results [compared to results from taking pictures]"</p> <p>"Hmm it might be kind of interesting to compare [PIV generated from the video] to [PIV generated from taking pictures]"</p> <p><b>Not knowing which images to choose for PIV analysis:</b> (<i>Looking at generated frames</i>) "Does it matter which ones I choose?"</p> <p>(<i>Looks at output</i>) "Hmmm...I'm wondering if I picked pictures farther away from each other, what that would do for me. ... Whoaaaaa" (New terrible output)</p> <p><b>Frustration with application delay in parsing video frames:</b> "It doesn't look like it has those frames yet;"</p> <p>(<i>audible sigh</i>) "We're just generating frames right now"</p> <p>"I'm wondering if I generated the frames from the right video because...hmm. ... So that still has not populated." (<i>After waiting to generate frames again</i>)</p>
Evidence of self-paced inquiry	<p><b>PIV inquiry :</b> "Anywhere the movement is the most simple, would maybe give the most accurate [results]"</p> <p>"How accurate do you think the vector output is? I would say, like on a scale from one to ten, just given the do it yourself component, that it's a not crazy laser or anything, I'm gonna give it a six out of ten, maybe a five and a half. ... Just based off the inexpensiveness of the equipment."</p> <p>"I took it from about five inches away, I wonder what it would be further away"</p>
Affective outcomes	<p><b>Unexpected interest in the aesthetics of PIV:</b> "That actually looks a lot different than I thought that it would, that's cool." (<i>Viewing the illuminated particles</i>)</p> <p>"You can see that [the illuminated flow field] really well, a lot better than I was expecting"</p>
No formal instruction in fluid mechanics	
Operation of mobile application	<p><b>Frustration: Not able to move back and forth within the app:</b> "That back button doesn't work for some reason..."</p> <p><b>Frustration: Image orientation change after processing data:</b> "I'm assuming that it's processing it, showing it this way [portrait], but I took them this way [landscape]. ... Even though I took them this way [landscape], it looks like it's looking at them this way. ... See, it rotates it opposite how I took it."</p>
Evidence of self-paced inquiry	<p><b>Fluid mechanics inquiry:</b> "It might be kind of interesting to see what it [jet flow] would look like if you could adjust the water pressure as well"</p> <p>"Looking at where the velocity is greatest ... I'm not sure if it would be right at, like, the mouth where it's coming out or where there's more turbulence. ... I would think maybe where you have these longer vectors, where it's going faster, is where the velocity is greatest." (Points to correct area)</p> <p>"I guess I just assumed that it would go straight down." (<i>Considering jet entrainment effects.</i>)</p> <p>"Most of the arrows, the vectors, are going this way, so I would assume the flow is going that way as well"</p>

(Continues)

TABLE 2 (Continued)

Category	Finding with representative data excerpts
Affective outcomes	<b>Excitement:</b> "Looking at this now, makes me more excited to start learning about it so I can put those things in context, having looked at this." ( <i>Gesturing to tank and phone.</i> )
Fundamental course in fluid mechanics	
Evidence of self-paced inquiry	<b>Fluid mechanics inquiry:</b> "I feel like as the particles move, it's going to contribute to changing [in the flow field]. It's like if you have something that's constantly running, it's going to have more of a stir in one spot than another. And those particles are going to help propel other particles to be moving as well"
Affective outcomes	<b>Initial apprehension:</b> "I didn't do very good in fluids..." <b>Engagement:</b> "This is so cool!"

video taken by the mobile device user or previously taken images or video that are uploaded to the mobile device.

It was also common for participants to not know how to select images for PIV processing. This finding led us to add user capability to review the images they select and precheck them for correlation. It is known that if the human eye can correlate two images (i.e., observe a displacement between two images when toggled back and forth) that PIV algorithms should also be able to correlate those images. Therefore, the capability for image pair review was added into the application. In addition, microcontent will be added into the application aimed at teaching learners how to select appropriate images for analysis. Last, it was common for participants to show and/or voice frustration with the time required to parse videos into images. This finding led directly to the development of new parsing algorithm that decreases the time for image parsing to within approximately 5–10 s.

Last, data identified *evidence of self-paced inquiry about PIV* as well as an affective outcome of *unexpected interest* in the esthetics of the laser illuminated and seeded flow was common across participants. Participants wondered aloud about the accuracy of the output, and seemed pleasantly surprised at how well the flow motion could be seen by the naked eye when illuminated by the laser light and at how interesting it looked to them. These findings support the inclusion of the *Learn about PIV* pathway in our GII and suggest that including microcontent in the application in the form of brief videos of seeded and illuminated flow may generate interest among learners in advance for conducting PIV flow experiments.

The participant having no formal fluids training expressed frustration with some basic operations of the application, such as the operating system back button not working and the image orientation of vector fields automatically flipping into portrait mode. These are important operational aspects of the application to refine, since we do not want to frustrate young learners who are,

most likely, adept at using mobile devices and have high expectations for the ways that mobile applications perform. This participant also provided evidence of engaging in self-paced inquiry while using the mobile application, particularly in relation to the fluid mechanics of the submerged jet and why the jet flow looked the way it did, which in some cases was different than they expected. Last, this participant expressed excitement about learning fluids concepts after having seen the PIV flow, saying: "*Looking at this now, makes me more excited to start learning about it [fluid mechanics] so I can put those things in context, having looked at this*" (gesturing to tank and phone).

The participant who had completed a fundamental course in fluids mechanics also engaged in fluid mechanics self-paced inquiry while using to mobile application to explore the jet flow. Interestingly, this participant focused more on the effects of the jet flow on the surrounding medium than on the jet flow itself, focusing on the jet causing "stir" (i.e., mixing or vorticity) and how particles in the flow have momentum and "propel" other particles to move. Findings also showed that this participant showed initial apprehension at using a fluids-related mobile tool based on their performance in the course ("I didn't do very good in fluids..."). Fortunately, their initial apprehension changed to engagement once the experiment got underway (This is so cool!), as if this participant began to see a different side of fluid mechanics altogether.

## 6 | CONCLUSION

This study describes Year 1 activities of a 3-year project to develop a mobile PIV learning tool for undergraduate and K-12 engineering education in formal and informal educational settings. Using a DBR approach, we completed preliminary design and development of a first-generation prototype of the mI-PIV learning tool, as well

as conducted four small-scale design studies to explore educational implementation factors as well as undergraduate learner use of the prototype tool in an unstructured learning environment.

Year 1 findings suggest that a mobile device and low power (i.e., 5 mW Class 3R that is safe for use without eye protection) cw laser can provide PIV output suitable for education. The same tool can provide measurement quality PIV output at higher laser power levels. In addition, our findings suggest that while undergraduate learners may initially respond differently to using the mI-PIV tool based on their prior experiences in fluid mechanics, as a group they tend to quickly become engaged in the aesthetics of the illuminated, seeded flow. Moreover, this engagement is seen to lead to excitement about the further study of fluid mechanics. Our findings support our initial hypothesis that *mI-PIV will interest students in the study of fluid mechanics and promote deeper understanding of fundamental fluid flow concepts and measurement techniques through hands-on experimentation and guided user microinstruction*, and also illuminate the importance of a high-quality application and interface design that will not frustrate learners who are adept at using mobile applications.

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**How to cite this article:** Minichiello A, Armijo D, Mukherjee S, et al. Developing a mobile application-based particle image velocimetry tool for enhanced teaching and learning in fluid mechanics: A design-based research approach. *Comput Appl Eng Educ.* 2020;1–21.  
<https://doi.org/10.1002/cae.22290>